Comparison between a moving bed bioreactor and a fixed bed bioreactor for biological phosphate removal and denitrification

H. J. Choi, A. H. Lee and S. M. Lee

ABSTRACT

Moving bed bioreactors (MBBR) and fixed bed bioreactors (FBBR) were compared for biological phosphorus removal and denitrification. The sorption denitrification P-elimination (S-DN-P) process was selected for this study. Results indicated that all nutrients were removed by the FBBR process compared with the MBBR process: 19.8% (total COD), 35.5% (filtered COD), 27.6% (BOD5), 62.2% (acetate), 78.5% (PO4-P), and 54.2% (NO3-N) in MBBR; 49.7% (total COD), 54.0% (filtered COD), 63.2% (BOD5), 99.6% (acetate), 98.6% (PO4-P), and 75.9% (NO3-N) in FBBR. The phosphate uptake and NO3-N decomposition in the FBBR process during the denitrification phase were much higher than for the MBBR process despite being of shorter duration. Results obtained from this study are helpful in elucidating the practical implications of using MBBR and FBBR for the removal of bio-P and denitrification from wastewater.

Key words | denitrification, FBBR, MBBR, phosphate removal, wastewater treatment

INTRODUCTION

There are many different biofilm systems in use for biological treatment of wastewater. Examples are trickling filters, rotating biological contactors, fixed media submerged biofilters, granular media biofilters, fluidized bed reactors. Moving bed bioreactors (MBBR) and fixed bed bioreactors (FBBR) were developed in the late 1980s and early 1990s to adopt the best features of the activated sludge process as well as the biofilter process (Ayati et al. 2007). The FBBR process is one of the extensively used systems in the removal of organic pollutants from wastewater because of its simple mechanical configuration, enduring high organic loading rate, low-energy requirements and operating costs (Borghei et al. 2008). On the other hand, the MBBR process proved to be very reliable for nitrogen removal because of the high volumetric loading rates and the low solids build-up in the reactor. One of the characteristic features of MBBR is the movement of media in fluids. The system is located somewhere between the activated sludge and the fixed bed biofilm system (Maurer et al. 2001). One important advantage of MBBR is that the filling fraction of biofilm media in the reactor is subjected to preferences. In order to move the media suspension freely, it is recommended that filling fractions should be below 70% (Rusten et al. 2006).

The objective of this study was comparison between a MBBR and a FBBR on biological P-removal and denitrification. The sorption denitrification P-eliminations (S-DN-P) process was selected for this experiment. The S-DN-P process can be subjected initially to the sorption (sorption phase) followed by the denitrification of the wastewater (i.e. denitrification phase). The denitrification phase was based on nitrate rather than oxygen respiration, i.e. the aerobic phase of the biological phosphorus removal (bio-P) process was replaced by an anoxic phase (Brandt et al. 2002).

MATERIALS AND METHODS

Chemical compositions of synthetic wastewater used for this experiment were determined as 210–390 mg/L of total chemical oxygen demand (TCOD), 10.52–37.94 mg/L NO3-N and 3.12–5.24 mg/L total phosphorus (TP). The schematic diagrams of the MBBR process and the FBBR process are shown in Figure 1(a) and (b), respectively. Both reactors were operated in the period from March to August.
The MBBR process, operated with 1,170 L of total volume, was prepared with a total volume of 1.5 m³ and 0.6 m³ of the filling material. The overall height and the height of the filling material in the MBBR were 2.2 and 1.9 m, respectively. Bio-flow media (Rauschert Steinbach GmbH, Steinbach am Wald, Germany), 9 mm diameter and 0.144 g/cm³ density, made of polyethylene (Figure 2(a)), were used as attached growth media. The inner part of the rings was divided into several sectors to increase the total biofilm surface (Choi et al. 2008). The FBBR process was operated with 1,205 L of total volume with 6–10 m³/m²/h of circulation rate. Approximately 40% porosity of the filter material with 25 cm (L) × 20 cm (H) × 7 mm (W), made of polyethylene (Figure 2(b)), was prepared. The filter was washed back every two or three days to prevent constipation of the biofilm. The media were rinsed several times with tap water to ensure the removal of the residual degradation products on the biofilm. The biofilms were adapted for one month for MBBR and FBBR.

The experiment was operated for 120 min (MBBR) and 60 min (FBBR) for the anaerobic sorption phase (S-phase) and 300 min (MBBR) and 275 min (FBBR) for the denitrification phase (DN-phase). The FBBR process was operated for a relatively shorter time than the MBBR process. The DN-phase was established by filling the emptied reactor with nitrifying water. The composition of the nitrifying water was 50 mg/L of NO₃-N (NaNO₃) and 20 mg/L of PO₄-P (KH₂PO₄ and K₂HPO₄) in raw wastewater. Samples were immediately filtered with a 0.45 μm membrane filter and PO₄-P, NO₃-N, NO₂-N, and acetate (AC) were analyzed using ion chromatography, whereas TP, TCOD and filtered chemical oxygen demands (FCOD) were measured photometrically with a spectrophotometer.

### RESULTS AND DISCUSSION

#### Comparison of substrate consumption as TCOD, FCOD, AC and BOD₅ in the S-phase

The sufficient sorption of organic substrates in the S-phase is a necessary precondition for complete denitrification. The TCOD was consumed 89.9 mg TCOD/L for MBBR (TCOD₀min – TCOD₆₀min) and 219.9 mg TCOD/L for FBBR (TCOD₀min – TCOD₆₀min) during the S-phase. The TCOD consumption rate of FBBR was noted as 29.9% higher than MBBR. Similarly, the FCOD and BOD₅ consumptions were obtained at 74.4 mg FCOD/L and 62.0 mg BOD₅/L for MBBR and 116.0 mg FCOD/L and 118.0 mg BOD₅/L for FBBR. The consumption of AC was 37.2 mg AC/L for MBBR and 74.7 mg AC/L for FBBR.

Figure 3 presents comparison of substrate consumption (in %) between MBBR and FBBR. Results indicated that all the nutrients were removed in the FBBR process much more than MBBR: 19.8% (TCOD), 35.5% (FCOD), 27.6% (BOD₅), 62.2% (AC), 78.5% (PO₄-P), 54.2% (NO₃-N) in MBBR; and 49.7% (TCOD), 54.0% (FCOD), 63.2% (BOD₅), 99.6% (AC), 98.6% (PO₄-P), 75.9% (NO₃-N) in FBBR. AC consumption and P-removal, especially, in the FBBR process were almost 100 and 98.6%, respectively.
The ratio efficiencies of FCOD/TCOD, BOD5/TCOD and AC/TCOD in the S-phase decreased 9.0%, 4.8%, 6.9% for MBBR; and 4.1%, 11.3%, 17.0% for FBBR (Table 1). This situation means, the FBBR process used more substrate than the MBBR process for biological P-removal and denitrification.

**Phosphate release and phosphate uptake**

The uptake ability of poly-P organisms largely depends on the activity of poly-P accumulating organisms (PAOs), which are used by the organic storage substances (i.e. PHB) in the previous anaerobic phase. The change of the linear/nonlinear concentration between anaerobic and aerobic/anoxic phases was also assessed by using the following general equation:

\[
\Delta P_{\text{uptake}} = a \cdot \Delta P_{\text{release}} + b
\]  

(1)

The coefficient ‘a’ represents the process of P-removal either by the bio-P mechanism or decomposition of polyhydroxyalkanoic acid (PHA) and the coefficient ‘b’ represents the indirect bio-P removal process (Abegglen et al. 2008; Adov et al. 2008). A high value of coefficient ‘b’ caused enhanced biologically induced precipitation. In other words, a high value of coefficient ‘b’ negatively affected the biological decomposition. In this experiment, coefficients ‘a’ and ‘b’ as well as \( R^2 \) were calculated as 1.59, 2.01, and 0.87 for MBBR and 1.22, 5.41, and 0.95 for FBBR, respectively. However, Brandt et al. (2002) tested a half-technical scale biofilter and moving bed reactor. They reported that the release and uptake of phosphate showed no clear tendency in the biofilter. This effect could be the accumulation of glycogen accumulating organisms which impair the metabolism of PAO.

**Phosphate release and substrate uptake in the S-phase**

The relationship of P-release and AC consumption in the S-phase can be described in the following equation for MBBR:

\[
Y_{\text{PO}_4-P/AC} = \frac{\Delta c(\text{PO}_4-P)}{\Delta c(Acetate)} = \frac{c_{120}(\text{PO}_4-P) - c_0(\text{PO}_4-P)}{c_0(Acetate) - c_{120}(Acetate)}
\]  

(2)

The relationship in FBBR can be expressed as \( c_{60} \) instead of \( c_{120} \). Such a relationship can also be formed for P-release/TCOD and P-release/FCOD. In this study, the values of the P-release and AC ratio for MBBR and FBBR were both 0.16 mg P/mg AC. This result showed that 6.4 mg of AC was consumed for 1 mg/L of P-release. The important characteristics of the influent stream in the bio-P-removal process included the P-release/TCOD and P-release/FCOD ratio along with the nutritional components. According to a previous report (Seviour et al. 2006), the appropriate value for the P-release/TCOD ratio may lie between 0.01 and 0.1 mg P/mg TCOD. In this study, the P-release/TCOD ratios for MBBR and FBBR were 0.06 and 0.04 mg P/mg TCOD, respectively. The MBBR showed a relatively higher P-release/TCOD ratio. Furthermore, the P-release/FCOD ratio was found to be lower for the MBBR (0.08) in comparison to the FBBR (0.11).

**Phosphate uptake and NO₃-N-decomposition in the DN-phase**

While comparing the level of P-uptake with the NO₃-N-decomposition in the DN-phase, it was noted that the complete reduction of nitrate to molecular nitrogen could not occur with the partial formation of nitrite (Carrera et al. 2004). Therefore, it was observed that NO₃-N-decomposition affects P-uptake in the DN-phase. It was reported to be around 0.47 for raw wastewater and 0.59 for dissolved wastewater (Choi et al. 2009). The calculation

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**Table 1** The ratio of substrate consumption in the sorption phase

<table>
<thead>
<tr>
<th>Reactors</th>
<th>FCOD/TCOD</th>
<th>BOD5/TCOD</th>
<th>Acetate/TCOD</th>
<th>FCOD/TCOD</th>
<th>BOD5/TCOD</th>
<th>Acetate/TCOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBBR</td>
<td>T = 0 min</td>
<td>T = 120 min</td>
<td></td>
<td>T = 0 min</td>
<td>T = 60 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46.1%</td>
<td>49.4%</td>
<td>13.1%</td>
<td>37.1%</td>
<td>44.6%</td>
<td>6.2%</td>
</tr>
<tr>
<td>FBBR</td>
<td>T = 0 min</td>
<td>T = 60 min</td>
<td></td>
<td>T = 0 min</td>
<td>T = 60 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48.6%</td>
<td>42.2%</td>
<td>17.0%</td>
<td>44.5%</td>
<td>30.9%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>
for the MBBR is according to the equation:

\[
\Delta C_{\text{NO}_3^-}^{\text{DN phase}} = C_{\text{NO}_3^-}^{t=0\min} - C_{\text{NO}_3^-}^{t=300\min}
\]

\[
= \frac{V_{\text{water}}}{V_{\text{Residual}}}
\]

The same formula used for FBBR changed only \( t = 300 \text{ min} \) to \( t = 275 \text{ min} \) in the DN-phase. In this study, the \( P/\text{NO}_3^-\) decomposition ratios were 0.39 mg P/mg \( \text{NO}_3^-\) and 0.46 mg P/mg \( \text{NO}_3^-\) for the MBBR and FBBR, respectively. The \( P/\text{NO}_3^-\) decomposition ratios with \( \text{NO}_2^-\) were 0.17 mg P/mg \( \text{O}_2\) for MBBR and 0.16 mg P/mg \( \text{O}_2\) for FBBR. \( P/\text{NO}_3^-\) decomposition ratio with \( \text{NO}_2^-\) was slightly different between the processes. It can be concluded that a large part of the microbial reactions was not based on the mechanism of enhanced biological phosphorus removal (EBPR), but the electron acceptor nitrate was predominantly used for other purposes, i.e. in particular, for growth or glycogen synthesis.

**Specific substrate consumption**

The initial concentrations \( (t = 0 \text{ min}) \) of \( \text{NO}_3^-\) for MBBR and FBBR in the DN-phase were 51.1 and 60.1 mg/L, respectively. The decomposed amounts of \( \text{NO}_3^-\) (\( \text{NO}_3^-\) \( t=0\min \) \> \( \text{NO}_3^-\) \( t=300\min \)) for MBBR and \( \text{NO}_3^-\) \( t=0\min \) \> \( \text{NO}_3^-\) \( t=275\min \) for FBBR) were 27.7 mg/L for MBBR and 45.6 mg/L for FBBR. The average decomposition of \( \text{NO}_3^-\) was 54.2% for MBBR and 75.9% for FBBR. The \( \text{NO}_3^-\) decomposition in MBBR possessed significantly lower values compared with FBBR. As shown in Table 2, the ratio of substrate consumption and \( \text{NO}_3^-\) decomposition possessed by the MBBR was compared with the FBBR. The ratio of TCOD/\( \text{NO}_3^-\) decomposition was 4.11 mg COD/mg \( \text{NO}_3^-\) for MBBR and 5.18 mg COD/mg \( \text{NO}_3^-\) for FBBR. The fact that the measured value of the TCOD/\( \text{NO}_3^-\) decomposition ratio lies within the range of 5–6 mg COD/mg \( \text{NO}_3^-\) was regarded as a normal range for most microbial metabolic processes.

**Table 2 | Ratio of substrate consumption and \( \text{NO}_3^-\) decomposition**

<table>
<thead>
<tr>
<th>Reators</th>
<th>TCOD/( \text{NO}_3^-) decomposition (mg COD/mg ( \text{NO}_3^-))</th>
<th>FCOD/( \text{NO}_3^-) decomposition (mg COD/mg ( \text{NO}_3^-))</th>
<th>AC/( \text{NO}_3^-) decomposition (mg COD/mg ( \text{NO}_3^-))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBBR</td>
<td>4.11</td>
<td>2.94</td>
<td>1.57</td>
</tr>
<tr>
<td>FBBR</td>
<td>5.18</td>
<td>2.05</td>
<td>1.56</td>
</tr>
</tbody>
</table>

The calculated ratios of FCOD/\( \text{NO}_3^-\) decomposition and AC/\( \text{NO}_3^-\) decomposition were 2.94 and 1.57 mg COD/mg \( \text{NO}_3^-\) for MBBR and 2.05 and 1.56 mg COD/mg \( \text{NO}_3^-\) for FBBR. In contrast with the TCOD/\( \text{NO}_3^-\) decomposition ratio, the ratio of AC/\( \text{NO}_3^-\) decomposition only had small differences; the AC/\( \text{NO}_3^-\) decomposition ratio, especially, had an almost identical value for both reactors.

**Influence of temperature on denitrification**

The MBBR and FBBR were operated in the period from March to April, and eight samples were collected during the S-phase and DN-phase of operations. The experiments were conducted at the average temperature of 13.8 °C (12.0–16.1) in the S-phase and 14.2 °C (12.4–15.3) in the DN-phase for MBBR and 22.2 °C (15.7–27.2) in the S-phase and 23.4 °C (15.5–31.5) in the DN-phase for FBBR. The relationship between the rate of denitrification and temperature is described with the van ‘t Hoff and Arrhenius equation:

\[
r_{\text{DN,T}} = r_{\text{DN,20}} \times \Theta^{(T-20)}
\]

\( r_{\text{DN,T}} \): denitrification rate dependent on temperature [mg/(L min)]; \( r_{\text{DN,20}} \): denitrification rate at 20 °C [mg/(L min)]; \( \Theta \): temperature factor (dimensionless).

The value of \( \Theta \) is dependent on the wastewater containing organic substrate and temperature. Different values were reported in the literature, for instance, a value of \( \Theta = 1.15 \) within the temperature range 5 to 20 °C for raw wastewater or a value of \( \Theta = 1.2 \) in the presence of endogenous storage compounds (Bever et al. 1993). Figure 4 shows the dependence of temperature on the denitrification rate in the case of \( \Theta = 1.17 \) for FBBR and the rate of denitrification at 20 °C was \( r_{\text{DN,20}} = 0.35 \text{ mg NO}_3^-\text{N}/(\text{L min}) \). In comparison, the rates of denitrification at 16 and 29 °C were \( r_{\text{DN,16}} = 0.21 \text{ mg NO}_3^-\text{N}/(\text{L min}) \) and \( r_{\text{DN,29}} = 1.65 \text{ mg NO}_3^-\text{N}/(\text{L min}) \), respectively. The rate of \( \text{NO}_3^-\)N...
decomposition at 29 °C was increased eight times more than at 16 °C. However, the rate of denitrification was not increased with increasing temperature for MBBR. One reason was that the temperature range was narrowed relatively and the other reason was the unfavorable relationship between the filling materials volume and wastewater volume. The denitrification rate depends not only on temperature but also on the population dynamic of microorganisms and wastewater composition.

CONCLUSIONS

This study compared the nutrient removal of two reactors, MBBR and FBBR, in wastewater. The FBBR process used more substrate (TCOD, FCOD, AC and BOD₅) than the MBBR process for biological P-removal and denitrification. Also, the P-uptake and NO₃⁻N-decomposition in the FBBR process during the DN-phase were much higher than for the MBBR process despite being of shorter duration. Furthermore, the P-release/FCOD ratio was found to be lower for the MBBR (0.08) in comparison with the FBBR (0.11). In contrast, the P-release/TCOD ratios for MBBR (0.06) showed a relatively higher value than that for FBBR (0.04). The NO₃⁻N-decomposition in FBBR (75.9%) possessed a significantly higher value compared to MBBR (54.2%). In contrast with the TCOD/NO₃⁻N-decomposition ratio, the ratio of AC/NO₃⁻N-decomposition only had small differences; the AC/NO₃⁻N-decomposition ratio, especially, had an almost identical value for both reactors. For FBBR, the rates of denitrification at 16 and 29 °C were 0.21 mg NO₃⁻N/(L min) and 1.65 mg NO₃⁻N/(L min), respectively.

The rate of NO₃⁻N decomposition at 29 °C was eight times more than at 16 °C. However, the rate of denitrification for MBBR was not increased with increasing temperature.

REFERENCES


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